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A study on muon content in gamma-ray initiated extensive air showers in correlation with shower age parameter

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Abstract : Correlation between muon content and shower age parameter in γ-ray initiated air showers is studied on the basis of the electron-photon cascade theory and through Monte Carlo simulation. It has been found that the ratio of muon size to electron size has a strong dependence on shower age parameter. The problem of muon anomaly in UHE gamma ray astronomy is discussed on the basis of present result

Keywords Muon content, γ-ray initiated air showers, Monte Carlo simulation

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1. Introduction

During last few years, a great effort has been made by several physicists to study the problem of total muon content in gamma ray intiated extensive air showers (EAS) in connection with the controversy over the possible existence of muon anomaly in observation of ultra high energy (UHE) radiation from stellar sources Recent observations [1] could not find any clear evidence of UHE steady or periodic signal from any discrete point sources. This failure of the detection may be due to highly sporadic nature of the sources. It is difficult to conclude that early positive observations are due to large statistical fluctuations because in a number of contemporary observations [2] of early eighties, excess EAS were observed from the said sources [3]. Moreover in the most of the positive observations, the excess EAS from the direction of Cygnus X-3 and Hercules X-1 were observed in phase with the orbital motion of the respective systems. The properties of the initiating particles of the detected excess showers are very tightly constrained and UHE gamma photons have to be assumed as primaries of such EAS. But the excess EAS did not have the photonic signature. The main indicator of a photonic origin for a shower is the relative low muon content in that shower [4]. However, a number of experimental evidence from UHE gamma-ray observations of different point sources suggest that gamma-ray initiated EAS's are by no means, dificient in muons. Samorski and Stamm [5] used the Kiel array to investigate the muon content in the excess air showers from the direction of Cygnus X-3. They reported that the muon content (threshold energy 2 GeV) at the excess showers from the direction of Cygnus X-3 is only slightly less (67%) than that obtained from a typical proton shower. Similar conclusion has been drawn by the Los Alamos group [6] for showers from the directions of Hercules X-1. In several observations [7], it was also found that the excess directional showers are-characterized by high shower age (s) value. However, the Monte Carlo simulation results [8] show that ages for the γ-ray initiated showers are nearly same as that of charged cosmic ray initiated showers. Since shower age represents a measure of longitudinal development of EAS and muon number (N_μ) does not change much with the atmospheric depth after the stage of maximum development of shower while shower size (N_e) decreases rapidly with the increase of shower age, the high muon content of the observed excess showers from point sources may be related with the high shower age value. No expression or detailed analysis exists at present, relating muon content in a γ-ray initiated shower with it's age parameter.

To examine this point, in the present work, an analysis has been made to study the dependence of muon content in γ-ray induced showers on shower size and shower age parameter on the basis of the electron-photon cascade theory and by Monte Carlo simulation.

2. Muon content in gamma-ray initiated showers

The first idea of a search for showers initiated by UHE gamma-rays was based on the fact that these showers should contain much fewer muons than normal ones. The muon component in hadron initiated showers originate from decay of charged pions created in interactions of hadron with the atmospheric nuclei. There are mainly three types of processes involved in the generation of muons in electromagnetic showers; direct creation of muon pairs, the production of heavy quarks (dominantly charms) and subsequent leptonic decays and photo production. Both theoretical calculation and Monte Carlo simulation results indicate that muon content in gamma-ray initiated showers should be more than one order of magnitude lower than that of normal showers.

In the hadron initiated showers, the energy dependence of the total muon content (N_μ) in a shower can be expressed as

$$N_\mu(>E_\mu) = \alpha E_0^\beta, \tag{1}$$

where E_0 is the energy of the shower initiating particle and E_μ is the threshold energy of the detected muons. Since the attenuation length for muons is very large [9] (~1200 gm/cm^2) for muon threshold energy 1 GeV), the values of the coefficient α and exponent β are almost independent on the level of observations after the shower reaches the maximum. Similar expression also holds for γ-ray initiated showers. Using the monte carlo simulation, results of Halzen *et al* [10] for showers having primary γ-ray photon the values of the parameters α and β are estimated as 4.73×10^{5} and 1.15 (when E_0 is in GeV) respectively for muon threshold energy 1 GeV. The value of the same parameters are obtained as 0.045 and 0.89 respectively from the Monte Carlo simulation results of Kalmykov *et al* [11] in which quarkgluon string model (QGSM) with the effect of semihard processes is assumed as high energy interaction model and proton is considered as primary. It is interesting to note that for showers initiated by γ-ray photon, the value of the exponent is greater than one while for proton showers, the value of the same parameter is less than one.

3. Cascade theory and the relation between muon content with shower age for showers with size N_e

According to the cascade theory, the development of electron-photon cascade is approximately described by the equations [12].

$$s_{||} \tag{2}$$

and $$N_e = (0.31/\sqrt{w})\exp[t(1-1.5\ln s_{||})] \tag{3}$$

where $w = \ln E/\varepsilon_0$, ε_0 is the critical energy (~81 MeV) and E is the energy of the cascade initiating particle, t is the atmospheric depth in unit of radiation length, $s_{||}$ is the longitudinal shower age and N_e is the shower size. Again $t = t_v$ sec. (z) where t_v is the vertical atmospheric depth at the observation level. Eliminating t from eq. (3) with the help of eq. (2), we get

$$w - 0.5\ln(w)/f(s_{||}) = \ln(N_e/.31)/f(s_{||}) \tag{4}$$

with $$f(s_{||}) = 2s\{1-1.5\ln(s_{||})\}/(3-s_{||}). \tag{5}$$

After simplifications, we get from eq. (1) and (3)

$$\ln(N_\mu) - \beta/2f(s_{||})\ln^2[N_\mu/\alpha)^{1/\beta}/\varepsilon_0] =$$
$$\beta/f(s_{||})\ln[N_e/.31) + \beta\ln(\varepsilon_0) + \ln(\alpha). \tag{6}$$

The above eq. is difficult to solve for N_μ. Since the values of β and $f(s_{||})$ are nearly one (for real values of s) the value of the 2nd term of the left hand side of eq. (5) is much smaller than the 1st term and we can approximate eq. (5) as

$$\ln(N_\mu) = \beta/f(s_{||})\ln(N_e/.31) + \beta/2f(s_{||})\ln\{1/f(s_{||})$$
$$\ln(N_e/.31)\} + \beta\ln(\varepsilon_0) + \ln(\alpha). \tag{7}$$

The above eq. gives the total muon content in a γ-ray induced shower as a function of shower age and shower size. The above relation is independent of the level of observation provided shower passes its maximum development.

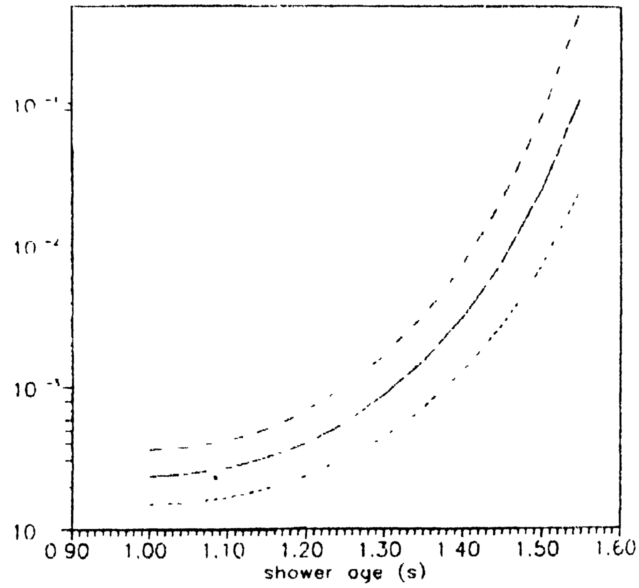

Figure 1. The variation of N_μ/N_e with longitudinal shower age for γ-ray initiated air showers for three different shower sizes at muon threshold energy 1 GeV. Small dash line corresponds to $N_e = 10^4$, solid line for $N_e = 10^5$ and big dash line for $N_e = 10^6$

The variation of the ratio of muon number to electron number with shower age for three different fixed shower sizes, $N_e = 10^4$, 10^5 and 10^6 are shown in Figure 1. It is clear from the Figure 1 that the ratio N_μ/N_e increases very sharply with age parameter.

4. Simulation result

In the present work, detail simulation of γ-ray showers has not been made. Instead, γ-ray showers were simulated following the procedure of Crewther and Protheroe [13]. Nearly 20,000 showers in the primary energy range 10^{15} to 10^{16} eV were generated assuming a power law integral energy spectrum ($J \sim E^{-1.6}$). The power index (-1.6) of the energy spectrum is assumed to be the same as that of cosmic ray particle spectrum. In air showers initiated by both γ-rays and nuclei, the major contribution on the fluctuation of cascade development profile is due to the fluctuation of the depth of first interaction point (t_2). Depths of first interaction were sampled from exponential distribution taking t_{int} (mean interaction length of γ-ray) is equal to 9/7 (in unit of radiation length). For remaining fluctuation, parametrisation of Crewther and Protherroe has been used. Thus, electron sizes were sampled from log-normal distribution. The mean of the distribution (μ) is given by

$$\mu(t_1) = \ln[N_1(t_1)] - \sigma^2/2, \quad (8)$$

where $t_1 = t - t_2$, and $N_1(t_1)$ is related to Griesen electron size (eq. 3) N_G by the expression.

$$N_1(t_1) = w/t_1 \, N_G(t_1) \, f(s) \quad (9)$$

with $f(s) = (0.88 + 0.146s(t_1)) \, [1 - \exp(-3.84s(t_1))]$ (10)

and the variance of the distribution is given by

$$\sigma = 0.157 - 0.0048w + 2.34[s(t_1) - 1]^2. \quad (11)$$

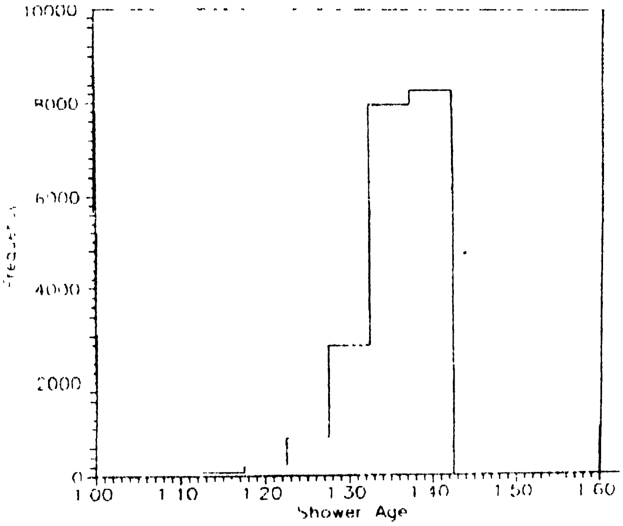

Figure 2. Distribution of shower age of simulated showers

The shower age distribution of the generated showers is determined and is shown in Figure 2. It is seen that the width of the distribution is quite small and no shower have age larger than 1.42.

No fluctuation, however, has been considered for muon component as at the sea level, the total muon content of a shower does not change much with depth of the atmosphere and total muon number in a shower of primary energy E has been calculated following eq. (1) with the help of simulation result of Halzen *et al.* [10]. For obtaining the result, generated showers were classified into small size bin and the average value of the ratio N_μ / N_e is determined for small shower age bin. Finally, variation of the ratio N_μ / N_e with shower age is plotted and shown in Figure 3. The simulation result can be parameterized by the expression

$$\ln(N_\mu / N_e) = a(s-1)^2 + b \quad (12)$$

with $a = 14.67$ and $b = 7.20$. The simulation result is compared with that given by eq. (7) i.e. with the prediction of cascade theory in the same figure

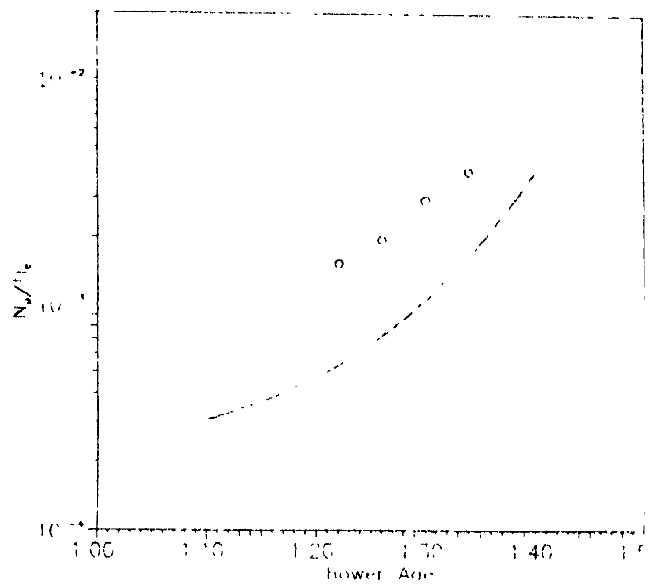

Figure 3. The comparison of the variation of N_μ / N_e with shower age at $N_e = 2 \times 10^5$ and at muon threshold energy 1 GeV according to cascade theory (solid line) with the same for Monte Carlo simulation results (data points)

5. Conclusions

In the present work, an analysis has been made to obtain a correlation between muon cascade and electron-photon cascade in γ-ray initiated showers. On the basis of electron-photon cascade theory, a relation has been derived relating muon size with shower size and shower age. The relation suggests that for a fixed shower size, muon content in a shower increases sharply with shower age. This is due to the fact that at a fixed shower size, to have a higher shower age value (i.e in the case of early development of shower in the atmosphere), the primary energy needs to be higher and for higher primary energy, muon size will be obviously higher.

Monte Carlo simulation study of γ-ray initiated showers has been made with the same objective as well as to compare with the theoretical result. Fluctuation in the shower development is incorporated using the parametrisation of Crewther and Protheroe [13] No fluctuation in muon content, however, has been considered. The simulation result also suggests a strong dependence of the ratio N_μ / N_e on shower age. When theoritical result eq (7) has been compared with the simulation result, it is found that the trend of the variation in both cases are same i.e. the ratio N_μ / N_e increases sharply with shower age parameter but the theoretically predicted variation appears to increase slightly faster than simulation result at shower size $N_e = 2 \times 10^5$.

Present analysis shows that with a increase of shower age from 1.25 to 1.35, the ratio of N_μ / N_e increases by three to four times. Interestingly, as mentioned earlier, in a number of observations, it was found that the excess showers from the direction of discrete point sources are really characterised by higher shower age value. So one can not rule out the possibility that the high muon content and high shower age value of the early detected directional showers are correlated. However, simulation resuls do not support the view that ages for γ-ray initiated showers are higher than the ages of hadronic showers (as also already mentioned in the introductory section). Present simulation result also shows that for γ-ray showers, the distribution of shower age parameter is quite narrow. It is thus very difficult to understand why the observed execess directional showers were older in age. More detailed study of the development of γ-ray initiated showers, specially in connection of their age value, is necessary.

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"Note added in proof After this paper was completed, the K G F group brought to our attention to another interesting observation by them in which the muon content in the simultaneous detected PeV energy of showers from the direction of Crab Nebula is found ~ 37% of that in normal cosmic ray showers [B S Acharya, M V S Rao, K Sivaprasad, B V Sreekantan and P R Vishwanath *Nature* **347** 364 (1990)] It is worth to mention that Crab Nebula is well known as a standard source in the TeV ray astronomy "